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NONRADIAL PULSATIONS OF HOT EVOLVED STARS+

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ABSTRACT

There are three classes of faint blue variable stars: the ZZ Ceti variables (DAV degenerate dwarfs), the DBV variables (DB degenerate dwarfs), and the GW Vir variables (DOV degenerate dwarfs). None of these classes of variable stars were known at the time of the last blue star meeting. Observational and theoretical studies of the ZZ Ceti variables, the DBV variables, and the GW Vir variables have shown them to be pulsating in nonradial g-modes. The cause of the pulsation has been determined for each class of variable star and, in all cases, also involves predictions of the stars envelope composition. The predictions are that the ZZ Ceti variables must have pure hydrogen surface layers, the DBV stars must have pure helium surface layers, and the GW Vir stars must have carbon and oxygen rich surface layers with less than 30% (by mass) of helium. Given these compositions, it is found that pulsation driving occurs as a result of the kappa and gamma effects operating in the partial ionization zones of either hydrogen or helium. In addition, a new driving mechanism, called convection blocking, also occurs in these variables. For the GW Vir variables, it is the kappa and gamma effects in the partial ionization regions of carbon and oxygen.

1. INTRODUCTION

In this paper I discuss our current knowledge about the nonradially pulsating degenerate and predegenerate variable stars. The ZZ Ceti variables inhabit a narrow instability strip with an effective temperature around 11,000K and a spread of about 1,000K

(Greenstein 1982). Their gravities are $\sim 10^8$ cm s^{-2} implying a mass of $0.6M_\odot$. The DB variables inhabit a hotter instability strip with an effective temperature of $\sim$25,000K and the boundaries of the instability strip are not well known. The GW Vir variables are much hotter with $T_e \sim 10^5$K. Their atmospheric composition has not, as yet, been determined. While they show no evidence for hydrogen in their atmospheres, they are too hot to set an upper limit to their hydrogen abundance. They show lines of helium, carbon, and oxygen and their ultraviolet spectra show numerous metal lines. One member of this class is the central star of a planetary nebula (K1-16) and all of the evidence indicates that the other members of the class were planetary nebula central stars in the recent past.

There have been a number of reviews of the properties of these variable stars (Van Horn 1980; Winget and Fontaine 1982; Van Horn 1984; Cox 1986; Winget 1986; Starrfield 1987) so that in this paper I will mainly discuss the recent results.

2. THE ZZ CETI VARIABLES

The first of the nonradially pulsating degenerate stars to be discovered was HL Tau-76 (Landolt 1968). It had a period of $\sim$750 sec and an amplitude of $\sim$0.3 mag. This period was much longer than the radial pulsation periods predicted for degenerate dwarfs and this result went unexplained for some years. In 1972, Chanmugam (1972) and

Warner and Robinson (1972) suggested that these stars must be pulsating in nonradial g modes since these were the only (either nonradial or radial) modes that had periods long enough to agree with the observations. Over the next few years, the Texas group came to the realization that there was an instability strip for DA dwarfs in a color interval around B-V~0.2. Later Greenstein's (1982) MCSP colors showed that they lay in the interval -0.41 < g-r < -0.29 (see also Green, Schmidt, and Leibert 1986). As a result of the searches of DA dwarfs in this color interval, there are currently at least 20 known ZZ Ceti stars which makes them one of the most numerous classes of variable stars in the galaxy (Winget 1986; Vauclair, Chevreton, and Dolez 1987).

However, it was not until the late 1970's that serious progress was made in identifying the pulsation driving. Starrfield, Cox, and Hodson (1979) used modern opacity tables and the linear, nonadiabatic, radial pulsation code of Castor (1971) to investigate DA envelopes for instabilities. Although they were successful and found that the envelopes were unstable to radial pulsations with very short periods, they used unrealistic compositions. They later redid these studies with a pure hydrogen composition and again found that the stars were unstable to radial pulsations (Starrfield, Cox, Hodson, and Clancy 1983; see also Saio, Winget, and Robinson 1983). They attributed the excitation mechanism to the well known kappa and gamma effects in the hydrogen partial ionization zone which lies close to the surface of these stars.

Meanwhile, Saio and Cox (1980) had developed a new numerical technique for the rapid analysis of the effects of linear, nonradial, nonadiabatic perturbations on stellar envelopes. Winget, et al. (1981, 1982) applied this technique (see also Dolez and Vauclair 1981 and Starrfield, et al. 1982) to a variety of stellar models. All of the above authors chose a mass of $0.6M_{o}$ and effective temperatures and luminosities in the range of the ZZ Ceti instability strip (See Winget and Fontaine 1982, Van Horn 1984, and Winget 1981, 1986). As summarized in Winget (1986): they found that the pulsations of the ZZ Ceti variables were caused by the partial ionization of hydrogen near the stellar surface and attributed the basic physical mechanism to the kappa and gamma effects operating near the base of the surface convective zone. They also found that there was an upper limit to the amount of mass of the hydrogen surface zone of $10^{-8}M_{o}$. If the surface hydrogen zone was more massive than this, the models were stable. This produced a strong disagreement with evolutionary calculations which predicted surface hydrogen masses of order $10^{-4}M_{o}$ or larger for all white dwarfs (Iben and Tutukov 1984). An attempt to resolve this controversy was made by Michaud and Fontaine (1984) who proposed that chemical diffusion of hydrogen into the deep interior could burn the hydrogen and reduce its abundance significantly below the evolutionary value. Further work on this subject has been done by Iben and MacDonald (1985,1986).

Finally, I note that the same theoretical analysis also predicted the existence of pulsators with pure helium atmospheres: the DBV variables. This prediction was borne out by the discovery by Winget, et al. (1982) that GD 385 was a pulsating variable star. Since that time three more such pulsators have been discovered (Winget 1986).

Nevertheless, the disagreement between pulsation and evolution theory was so severe that it seemed important to redo the work of Winget, et al. Such a study has now been done by Cox, et al. (1987) who used both the Saio and Cox (1980) code and a new Lagrangian code developed by Pesnell (1987). Although the quanitative agreement between the two codes is not terribly good, the qualitative results are in good agreement. They find a blue edge at about 11,500K for models which assume very efficient convection: $1/h_p \sim 2$ to 3. The blue edge does not depend on the amount of hydrogen envelope mass and, in fact, stellar models with $M_e = 10^{-4} M_o$ are pulsationally unstable. This completely removes the theoretical discrepancy between the evolution and pulsation calculations.

Another important result of Cox, et al. is that one of the causes of the instability is neither the kappa nor the gamma mechanism, resulting from the partial ionization of hydrogen, but is a new physical effect which they call convection blocking. In essence, the interaction of pulsation and convection can act to block the flow of energy in a compression or release it in an expansion just like the normal kappa and gamma mechanisms. The strongest evidence for the existence of this new mechanism is that the pulsation driving in the envelopes always occurs at the bottom of the convective region even when the temperature there exceeds 10^5K, which is much too hot for hydrogen pulsation driving. At the blue edge both convection blocking and the kappa and gamma effects are both operating. Unfortunately, this means that a correct theory of the ZZ Ceti instability strip awaits a time dependant pulsation-convection theory. They also found that this same mechanism was occurring in all of the previous calculations but was not interpreted correctly.

Finally, Cox, et al. also redid their analysis of the radial instability in the ZZ Ceti variables and again found that these stars were unstable to high order radial modes with periods of less that a second. As for the nonradial modes, driving was caused both by convection blocking and also the kappa and gamma effects. At this time no star has been found to be pulsating in radial modes (Robinson 1985). Cox, et al. speculate that the interaction between convection and pulsation may be responsible for stabilizing these stars.

3. THE PULSATING DB STARS

Currently there are 4 known pulsators with pure helium atmospheres (Winget 1986) and their discovery is a direct result of the theoretical predictions of Winget (1981). Both ultraviolet and optical atmospheric analyses have been performed on these stars and the instability strip ranges from an effective temperature of 24,000K to about 28,000K (Liebert, et al. 1986). However, the boundaries are rather uncertain and probably could vary by as much as 2,000K (Liebert, et al. 1986). Koester, et al. (1985) find a somewhat cooler instability strip.

Theoretical analyses of these stars have been performed by Winget (1986) and by Cox, et al.(1987). These two groups are in essential agreement but with some of the same differences in interpretation already mentioned for the ZZ Ceti variables. Just as in the ZZ Ceti variables, they find that driving occurs at the bottom of the surface convection zone and attribute it to the effect of convection blocking. The cause of instability is ultimately the partial ionization region of helium and hydrogen cannot be present in the driving region to rather stringent limits because hydrogen can easily poison the pulsations in this temperature range. If there were any hydrogen it would float to the surface on a rather rapid time scale. Cox et al. also proposed that some DAV appearing stars might be found in the DBV instability strip. They would have a very thin layer of hydrogen overlying the deeper helium layers. It was also found for these variables that very efficient convection was necessary in order for the observed instability strip to agree with the theoretical instability strip. In fact, Cox et al. found that they had to assume $1/h_p \sim 3$ in order to obtain a blue edge ~27,000K.

4. THE GW VIR VARIABLES

The first member of this class of variable stars was discovered at the MMT by McGraw and Starrfield (McGraw, et al. 1979). It was found to be pulsating in a number of modes with periods around 500 seconds. Spectroscopic studies showed no evidence for any hydrogen in the atmosphere, g $\sim 10^7$ to 10^8 cm s^{-2}, and that its effective temperature exceeded 10^5K. This estimate of its temperature was later confirmed by Exosat studies (Barstow, et al. 1986). In other studies, Winget, et al. (1985) have measured a period change in GW Vir of -2.34×10^{-14} s/s. This has now been interpreted by Kawaler, Hansen, and Winget (1985) as caused by a shrinking, rotating star pulsating in a low order l=3 mode (l is the number of node lines on the surface). They obtain a rotation velocity of $\sim 35 - 50$ km s^{-1} which does not seem unreasonable for a white dwarf. Kawaler (1986) has done an analysis of the period spectrum of GW Vir and finds 8 periods are present and that P_o is either 8.8 s or 21.1 s. Since P_o depends on l(l+1), this star is pulsating in either the l=1 or l=3 mode.

Other pulsating members of this class have been discussed by Grauer and Bond (1984) and Bond, et al. (1984). The most luminous member of the class is the central star of the planetary nebula K1-16 and it has a lower gravity than the other members of the class. In addition, it is pulsating at periods of $\sim$1700 sec which are much longer than those found in GW Vir. Kawaler, et al. (1986) have investigated K1-16 for the epsilon mechanism but find that although an instability exists, the periods are too short to agree with those observed in K1-16 or the other GW Vir variables.

Starrfield, et al. (1983; 1984; 1985; 1987, in preparation) identified the pulsation driving mechanism as the partial ionization of the last two electrons of both carbon and oxygen. Both the Saio and Cox (1980) and the Pesnell (1986) codes have been used to analyze stellar envelopes in the effective temperature range from 70,000K to 150,000K (and hotter). The mass of the star was assumed to be $0.6M_{\odot}$ and the composition of the envelope was assumed to be either half helium and half carbon (by mass), pure carbon, half carbon and half oxygen, 90% oxygen and 10% carbon, or various combinations of helium, carbon, and oxygen. They found instability strips for these stars in the above temperature range. They also predicted that if GW Vir were as hot as suggested by the Xray observations, then a significant amount of oxygen was required at the surface in order for it to pulsate. This prediction was confirmed by Sion, Liebert, and Starrfield (1985) who obtained spectra in the optical ultraviolet for GW Vir, and two other GW Vir stars, and found oxygen absorption lines present in the spectrum. The actual abundance of oxygen is unknown since, as yet, no abundance analysis has been done for these stars. A recent study of K1-16 has found oxygen lines present in the ultraviolet spectrum but they are in emission since it is the central star of a planetary nebula and is still (possibly) losing mass.

Starrfield et al. (1985; and in preparation) have also done a linear, nonadiabatic, nonradial analysis of K1-16 and found instability strips for this star at high luminosity. They used the same compositions and stellar mass as in the GW Vir studies but assumed that the star was on the high luminosity part of the evolutionary track to the white dwarf region of the HR diagram and that it was evolving rapidly to higher effective temperatures. In order for K1-16 to be pulsating at periods of ~1700 sec it must have T_e ~ 130,000K. Unfortunately, the temperature range of the instability strip is very broad and it will be impossible to predict the effective temperature from the theoretical analysis. They have also studied models with different masses and find regions of instability ranging from ~120,000K to more than 200,000K. There is no overlap in the periods of the unstable modes for models with different luminosities.

Finally, in a recent study Starrfield, Cox, and Pesnell (1987, in preparation) have analyzed a series of $0.6M_{\odot}$ models with surface compositions of various amounts of helium plus equal amounts of carbon and oxygen. They find, for T_e ~90,000K to 100,000K, that if there is more than 30% helium by mass, the stars will be stable. The number of unstable modes increases as the amount of helium increases.

5. CONCLUSIONS

The observational studies of these stars have shown both that they are pulsating in nonradial g modes and these modes are of low order in l (the number of node lines on the surface) and high order in k (the number of nodes in the radial eigenvector). The principal argument in favor of these conclusions is that the periods calculated for stellar models in the observed temperature range are quite close to those that are observed. These conclusions will be strengthened when there has been a successful mode identification.

The discovery and analysis of these stars has markedly improved our understanding of the last stages of evolution of stars like the sun. In order to analyze these stars and demonstrate that they are pulsating in nonradial modes, it was necessary to develop new numerical techniques and use the latest stellar opacities and equations of state. In addition, in order to improve the correspondence between theory and observations it was necessary to apply diffusion theory to the outer envelopes of DA white dwarfs. Now it appears that a time dependant theory of the interaction between convection and pulsation will have to be developed in order to determine the theoretical boundaries of the ZZ Ceti and DBV instability strips. Finally, it is already clear that the existence of these variables in the observed temperature range requires that convection be very efficient.

The theoretical analysis of these stars has provided us with two new pulsation driving mechanisms. In the case of both the ZZ Ceti and DBV variables it is "convection blocking" which occurs as a result of the interaction between convection and pulsation. Detailed analysis of the driving regions in both classes of variables shows that convection cannot adjust instantaneously to either a compression or an expansion and the result is a blocking or release of energy out of phase with the envelope motions. This is analogous to the normal kappa and gamma mechanisms which operate in the Cepheids or RR Lyrae variables but in their case it is the partial ionization of hydrogen and helium that excites the pulsations.

In the case of the GW Vir variables it is the action of a kappa and gamma mechanism that drives the pulsations, but for these variables it is the partial ionization of carbon and oxygen at very near the stellar surface that causes the pulsational instability and evidence has now been obtained that these stars have oxygen present at the surface. This implies that these stars have probably suffered a great deal of mass loss in order for them to have eliminated their entire hydrogen and most of their helium burning layers.

The pulsational analyses have placed these stars in regions of the HR diagram where evolution is proceeding very rapidly. In fact, a period change has already been measured for GW Vir and the value is as predicted for post planetary nebula stars that have just evolved onto a white dwarf cooling curve. The observed value of the period change can be explained by a rotating, cooling star with $T_e \sim 10^5$K. The central star of the planetary nebula, K1-16, should be evolving more rapidly than GW Vir and efforts to measure a period change in this star are in progress but are hampered by the fact that the period is changing so rapidly that it may not be possible to match observations from one season to another (Grauer, et al. 1986).

Finally, the observations of these stars show that there is helium present in the surface layers. The fraction of helium cannot exceed about 30% by mass, otherwise the stars cannot pulsate. However, with time the helium will float to the surface and halt the pulsations. Nevertheless, as the star cools it will pass through the DBV instability strip and again become a pulsating variable star.

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